Requirements for the Main Injector BPM upgrade

Version 1.0

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April 22, 2005

Introduction

The Fermilab Main Injector is a rapid cycle accelerator with an injection energy of 8.9 GeV and an extraction energy of up to 150 GeV. It serves multiple purposes, providing protons for anti-proton production, fixed target experiments and Tevatron injections. It receives anti-protons from the Accumulator and accelerate them for Tevatron collider operation. Also it serves as interface between the Recycler Ring and the rest of the accelerator complex. Antiproton transfers in and out of the Recycler Ring take place through two transfer lines connecting the Recycler to the Main Injector.

The Main Injector is seven times in circumference (3319.42 meter) of the Booster (474.2m) from which it accepts the protons, and is slightly larger than half the circumference of the Tevatron (2000π meter) to which it transfers both the protons and the anti-protons. Only six Booster cycles (batches) are utilized to fill the MI, allowing rest of the space for the abort gap. The harmonic numbers of the Booster, MI and the Tevatron are 84, 588 (84X7), and 1113 (84X13.25) respectively. Transfers from the Booster and to the Tevatron are bucket to bucket transfers at a frequency close to 53 MHz. Anti-protons transfers from the Accumulator and transfers to or from the Recycler Ring instead happen in 2.5 MHz buckets.

The Main Injector accelerates protons from 8.9 GeV to 120GeV for anti-proton production, for fast single turn extraction for dedicated neutrino experiments (i.e. NuMI/MINOS) and for slow resonant extraction to fixed target experimental areas. For collider operations, it accelerates protons from the Booster from 8.9 GeV to 150 GeV, and anti-protons from the Accumulator or the Recycler Ring from 8.9 GeV to 150 GeV, injecting them into the Tevatron. Moreover it is used to transfer anti-protons from the Accumulator to the Recycler Ring at 8.9 GeV.

Even if the Main Injector operation includes acceleration of both protons and anti-protons, they are never present simultaneously in the ring.

Each of the different modes of operation of the Main Injector described above, together with possible machine studies, are identified by Tevatron Clock events (TCLK), which act as machine cycle resets (start of cycle). The different cycles are controlled and synchronized by the Timeline Generator system (TLG). For example, in a 60 s cycle, the TLG specifies the sequence of the Main Injector cycle resets, the associated Main Injector state (used i.e. by the Low Level RF system) broadcasted in MDAT (I:MDAT56), and the duration of the cycles. In case of proton transfers from the Booster, it also specifies the number of Booster injections (batches), and, through the associated Booster TCLK event, the number of bunches and their intensity.

Table 1 summarizes the Main Injector current operational modes, the corresponding TCLK cycle reset events, the RF frequencies involved, the approximate cycle lengths and energy sweeps. It is worth noting that cycle lengths are relatively short, due to the fast acceleration rate of the Main Injector. Beam injection into the Main Injector can happen as fast as ~ 50 ms after a TCLK reset event.

Operational Modes	TCLK	RF frequency	Cycle Length	Energy sweep
Anti-proton production and/or Neutrino Experiments	**$29, $23**	**53 MHz**	**1.6 – 2.0 s**	**8.9 - 120 GeV**
Slow extraction to fixed-target experiment (and anti-proton production)	**$21**	**53 MHz**	**2.6 – 6.0 s**	**8.9 - 120 GeV**
Proton transfers to the Tevatron	**$2B**	**53 MHz**	**3.65 s**	**8.9 - 150 GeV**
Anti-proton transfers from Accumulator to Recycler	**$2D**	**2.5 MHz**	**4.9 s**	**8.9 GeV**
Anti-proton transfers from Accumulator/Recycler to Tevatron	**$2A**	**2.5 and 53 MHz**	**7.8 – 12 s**	**8.9 - 150 GeV**

Table 1: Main Injector current Operational Modes

The present system

The Main Injector has four BPM detectors per betatron wavelength in both the horizontal and the vertical planes. There are a total of 208 BPMs for the 3320 m ring. Out of these, 203 are MI style ring BPMs, and are located in the downstream end of every MI quadrupole. The other 5 are wide aperture BPMs located at Q101, Q402, Q522, Q608 and Q620 locations.

The BPM detectors in MI consist of four transmission line strips, or strip-lines, located on the perimeter of the beam pipe. The strip-lines have a width of 12.7 mm and are positioned at a distance of 46.7 mm horizontally and 44.5 mm vertically, center to center. The pick-up has a characteristic impedance of 50Ω, determined by the strip and the beam pipe dimensions. The RF module input impedance is matched to 50Ω within a 5 MHz bandwidth centered at 53MHz. The outputs are combined in pairs externally to form either a horizontal or a vertical detector. Each strip-line is shorted at one end and connected to a ceramic feed-through at the other end, which makes these BPMs non-directional. At present any BPM measures either the horizontal or the vertical position per cycle at each quads. It can be easily switched to the orthogonal mode.

The wide aperture BPMs, with 6” long plates and a 4.625” aperture, are located adjacent to the Lambertson magnets and are mounted external to the quadrupole magnets.

The Abort line of the Main Injector is instrumented with 3 large aperture BPMs, each one providing both a horizontal and vertical position measurement.

Scope of the Project

The scope of the upgrade includes all the BPM detectors installed in the Main Injector and the MI Abort line.

The present switching capability between horizontal and vertical position measurements of the detectors in the MI ring will not be retained in the upgraded system. Horizontal only measurements are required at focusing quadrupole locations and vertical only measurements at defocusing quadrupole locations.

The upgrade will make use of the existing pick-ups and cables. This is true for all locations except at the Q101, Q222, Q321, Q402, Q522, Q608 and Q620 locations in the Main Injector ring, where large aperture quadrupole magnets, presently under construction, will be installed. In these specific locations the present BPM detectors will be replaced by larger aperture ones compatible with the aperture of the new quadrupole magnets. The new BPM detectors in these locations shall be capable of simultaneous horizontal and vertical position measurements.

The project includes electronics and software necessary to measure beam positions and relative beam intensity utilizing the BPM detectors. Also included are relevant documentation and user guides to describe, use and maintain the system.

The project includes diagnostics to verify the performance of the electronics and to maintain the system within the specification requirements.

Beam time structures, beam modes and dynamic ranges

At any particular instance of time there will be only one kind of beam in the MI. It will be either protons or anti-protons. The beam energy can vary between 8.9 GeV to 150 GeV. The time structure of the beam can be:

1. 53 MHz - Protons or anti-protons. From 1 bunch up to a full batch of 84 bunches in successive 53 MHz buckets (19ns apart). The 95% bunch length varies between 1 ns, at transition and at 120 GeV after bunch rotation for anti-proton stacking, to 10 ns for single coalesced bunches. Up to 6 batches, each one of 84 bunches, can be loaded in the MI.
2. 2.5 MHz - Protons or anti-protons. 1 to 4 bunches in successive 2.5 MHz RF buckets (396 ns spacing). 95% bunch lengths range from 100 to 200 ns at 8GeV. With the implementation of 2.5 MHz anti-proton acceleration, bunch lengths will shrink down to 40 ns at 27 GeV.

For each beam RF structure of the Main Injector operational modes, we will specify bunch arrangements, lengths and intensities.

1. Protons for anti-proton stacking and fixed target ($29, $23, $21)
   One up to 6 Booster batches, however spaced, are injected in MI at 8.9 GeV and accelerated up to 120 GeV. Beam is extracted in a single turn to the anti-proton production target and to dedicated neutrino experiments or in a slow resonant extraction mode (slow spill) to fixed target experimental areas. Mixed-mode cycles are present in

MI where beam is successively extracted to the anti-proton source and to the neutrino experiments.

Energy	8 to 120 GeV
Bunch RF	53 MHz
Bunch structure	84 bunches/batch, up to 6 batches however spaced
Bunch length (at 95%)	6 ns (8 GeV) 1.5 ns (150 GeV, after bunch rotation)
Intensity/bunch	5E9 to 130E9

Table 2: Protons for anti-proton stacking and fixed target

2. Proton transfers to the Tevatron ($2B)
   a. Tune-up

Energy	8 to 150 GeV
Bunch RF	53 MHz
Bunch structure	30 to 84 uncoalesced bunches
Bunch length (at 95%)	6 ns (8 GeV) 2.5 ns (150 GeV)
Intensity/bunch	10E9 to 100E9

Table 3: Proton transfers to the Tevatron

   b. Proton transfers for collider operation

Energy	8 to 150 GeV
Bunch RF	53 MHz
Bunch structure	5-9 bunches, coalesced into one bunch at 150 GeV
Bunch length (at 95%)	6 ns (8 GeV) 2.5 ns (150 GeV uncoalesced) 10ns (150 GeV coalesced)
Intensity/bunch	30E9 to 100E9 (uncoalesced) 50E9 to 400E9 (coalesced)

Table 4: Proton transfers for collider operation

3. Anti-protons transfers from Accumulator/Recycler Ring ($2A, $2E, $2D)

Energy	8 to 27 GeV
Bunch RF	2.5 MHz
Bunch structure	4 consecutive bunches
Bunch length (at 95%)	100-200 ns (8GeV) 40 ns (27 GeV)
Intensity/bunch	5E9 to 150E9

Table 5: Anti-proton transfers from Accumulator/Recycler Ring

4. Anti-proton transfers to the Tevatron ($2A, $2E)

Energy	8 to 150 GeV
Bunch RF	53 MHz
Bunch structure	4 consecutive groups, spaced by 400 ns, of typically 5 (up to 9) 53 MHz bunches, coalesced into a single bunch at 150 GeV
Bunch length (at 95%)	8.5 ns (8 GeV) 3.5 ns (150 GeV uncoalesced) 10 ns (150 GeV coalesced)
Intensity/bunch	5E9 (uncoalesced)

	10E9 to 150E9 (coalesced)

Table 6: Anti-proton transfers to the Tevatron

Measurement Specifications

The upgraded BPM system will provide a single ensemble position measurement of the beam present in the machine for each one of the operating modes described above. In particular the system should be capable of measuring beam positions with 6 batches loaded in the MI, however spaced.

The upgraded BPM system will also provide a beam intensity measurement from the magnitude of the sum of the plate signals for each BPM. This measurement will provide a "relative" intensity measurement between different BPMs and an intensity variation with time for each one of the BPMs. BPM-to-BPM scaling capability should be incorporated in the system to equalize the response of the different BPMs.

The system will operate in both a high and low bandwidth modes. High bandwidth is needed for measurements that require single turn resolution. Narrow bandwidth will be used for measurements that do not need single turn resolution and represent an average position. The system will need to be switched between wide and narrow band operation in a given cycle with a minimum interruption in data acquisition (less than ~ 10 ms).

Beam in the Main Injector will either be bunched in 53 MHz or 2.5 MHz. The BPM system is expected to make measurements in all modes with either bunch structure. The system will be able to be switched from one bunch structure to the other structure in a given cycle with a minimum interruption in data acquisition (less than ~ 10 ms).

For 53 MHz multi-batch operation and for 2.5 MHz anti-proton transfers, the system should be able to provide, if requested, a batch-by-batch and a bunch-by-bunch measurement, respectively. These batch-by-batch or bunch-by-bunch measurements do not need to meet the resolution specifications, but they are useful for diagnostic purposes.

We will now proceed to define the quantities upon which we will serve as a base for the BPM measurement specifications.

a) Measurement range. This is defined as the range of positions, relative to the BPM center, over which the BPM measurement must be valid and meet the accuracy requirements.
b) Absolute position accuracy. This determines how well the position of the beam is measured with respect to the survey center-line. This is limited by a number of factors including alignment, calibration, cable attenuation and noise.
c) Relative position accuracy. This determines how well the displacement of the beam is measured over the measurement range. This requirement does not include offset errors, but does set limits on the scale errors, non-linearities and random errors.
d) Position resolution. This is a requirement on the smallest change in beam position that the BPM can reliably measure.
e) Position linearity. This is a requirement on the linearity of the BPM response to orbit changes over the measurement range. The linearity is defined as the difference between the measured BPM position and the slope of the BPM response at the center of the BPM.

f) Long-term position stability. This is a requirement on the BPM system ability to give the same position value for the same beam position and intensity over time.
g) Intensity accuracy.

Tables 7 and 8 summarize measurement specifications for 53 MHz and 2.5 MHz bunch structures, respectively.

Measurement specifications	**53 MHz bunch structure**
Measurement range	±25 mm, ±30 mm for large aperture BPMs
Absolute position accuracy	1 mm + 5% of actual beam position
Relative position accuracy (3 σ)	5% of actual beam position
Position resolution (3 σ)	0.05 mm (0.1 mm)
Position linearity	within 1.5% of the slope of the BPM response at the center of the BPM over ±15 mm
Long-term position stability	0.2 mm
Intensity accuracy	10% (20%)

Table 7: Measurement specifications for 53 MHz bunch structure, low bandwidth mode. Values in parenthesis are for high bandwidth mode, with single turn resolution.

Measurement specifications	**Anti-protons of nominal intensity (>20E9/bunch), 2.5 MHz bunch structure**	**Anti-protons at low intensity (<20E9/bunch), 2.5 MHz bunch structure**
Measurement range	±25 mm, ±30 mm for large aperture BPMs	±25 mm, ±30 mm for large aperture BPMs
Absolute position accuracy	1 mm + 10% of actual beam position	1 mm + 20% of actual beam position
Relative position accuracy (3 σ)	10% of actual beam position	20% of actual beam position
Position resolution (3 σ)	0.3 mm (0.5 mm)	0.5 mm
Long-term position stability	0.5 mm	N/A
Intensity accuracy	20% (30%)	30%

Table 8: Measurement specifications for 2.5 MHz bunch structure, low bandwidth mode. Values in parenthesis are for high bandwidth mode, with single turn resolution.

Data Acquisition

The upgraded BPM system is expected to provide position and intensity information to the Accelerator control system for each Main Injector TCLK ramp reset. It is expected the each TCLK ramp reset will have buffers in the front-end that will contain the data collected from the last reset.

As described above the BPM system will operate in both a high and low bandwidth modes. High bandwidth is needed for measurements that require single turn resolution. The system will need to be switched between wide and narrow band operation in a given cycle with a minimum interruption in data acquisition. There will be several different data types in the new BPM system. These types are listed as follows:

- Flash Frame. A single turn orbit measurement, performed in high bandwidth mode.
- Turn By Turn. A measurement of the orbit on every turn for a specified number of turns, performed in high bandwidth mode.
- Averaged orbit: An average of some number of Turn by Turn measurements.
- Closed orbit. A narrow bandwidth measurement taken at a specific time. This measurement occurs once per cycle.
- Profile frame. A narrow bandwidth measurement taken at a specific time. This measurement can occur many times per cycle.

The new system will also support fast time plots of the BPM channels and will not have limits on the number on BPM channels that can be plotted from a given front end.

The new BPM system will have two different triggering modes for sampling the beam. The beam sample bucket will either be user specified or the system will generate its own trigger in a self triggered mode. When the user specifies the machine bucket, the specification will be relative to the Main Injector Beam Sync (MIBS) $AA event at the MI60 service building. When the user specifies the self triggered mode, the BPM system is expected to generate its own trigger to sample the beam. Currently this self trigger is accomplished in the current BPM system by looking for a gap in the beam a setting a sample relative to the leading edge of a batch.

For each MI reset there will be a user specified data acquisition definition. This definition will specify the filter configuration, the data type, and the timing. Due to the multi function nature of the MI the BPM system is expected to be able to switch between both filter and data type during a given cycle with minimal data loss.

The end of beam event in the MI, TCKL $26, presents an ideal time to collect the BPM information. Typically there will be .5 seconds of dead time after the end of beam event.

Figure 1 represents an example of a data acquisition definition for a cycle, in this case stacking. This example represents the typical type of data taken with the current BPM system that is used for tuning beam to the anti-proton target for stacking. In this example, the BPM system is prepared for data on MI TCLK $29 event. The filters are set to 53MHz in the wide band mode. The system will then wait for beam to be injected from the Booster, TCLK $28 is triggered on Booster extraction. When beam is injected into MI the system will collect turn by turn data for 1024 turns and will self trigger. At 0.02 seconds after $29 the system will set the filter to 53 MHz in the narrow band mode. It will then wait for TLCK $7B to write a display frame or event $7A to write profile frames. At .85 seconds, neat the end of the cycle, the filters are set to 53 Mhz in the wide band mode. A turn by turn is then triggered for 2048 turns and sampled at bucket 320. Finally the system waits for the end of cycle, event $26, and collects the data.

Stacking Default

ROW	TYPE	SIGNAL	MESSAGE	DATUM1	DATUM2	DATUM3	DATUM4
1	Event	Reset29	PrepareForBeam				
2	Continue		SetFilter	53 Mhz	Wide		
3	Event	BooPInject	TriggerTBT	1024 Pts	SelfTrigger		
4	Delay	.02 sec	SetFilter	53	Narrow		
5	Event	ClosedOrbitTrigger	MeasureOrbit				
6	Delay	.85	SetFilter	53	Wide		
7	Continue		TriggerTBT	2048	SampleBucket	320	
8	Event	EndCycle	CollectData				
9							
10							

Figure 1: Example of a data acquisition definition on a stacking cycle.

End User Applications

Current System

I37 BPM Control Parameters

I38 BPM/BLM Hardware Tests

I39 BPM/ BLM Plots /List

I42 Tune From TBT BPM

I50 MI Orbit / C453

I52 BO=>MI Injection Closure

I73 MI Measure Chromaticity

I75 MI Quad Move

I92 TBT Data/Analysis

T117 Tev Orbit Closure

Maintenance and Calibration

The new MI BPM system should be equipped with a test system to diagnose problems in the raw signals from the tunnel and at every stage in the electronic front-end. Test signals should be provided to verify the performance of the electronics. They should also perform as a calibration tool able to maintain the system within the specification requirements.